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TITLE: TRANSPORT SIMULATIONS OF THE OSCILLATING FIELD CURRENT DRIVE EXPERIMENT IN THE ZT-40M REVERSED FIELD PINCH

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TRANSPORT SIMULATIONS OF THE OSCILLATING FIELD CURRENT DRIVE EXPERIMENT IN THE ZT-40M REVERSED FIELD PINCH

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I. INTRODUCTION

Oscillating Field Current Drive (OFCD) as originally proposed by Bevir and Gray[1] is based on the premise that in order to sustain a relaxing Reversed Field Pinch (RFP) plasma, one needs only to supply magnetic helicity at the same rate it is consumed. The helicity balance equation reads as[1,2,3]

$$\frac{dK}{dt} = 2\phi V_z - 2\int_v \mathbf{E}\cdot\mathbf{B}dv, \tag{1}$$

where the term on the left-hand side represents the rate of change of helicity inside the vacuum vessel, the integral is the rate of dissipation of helicity in the plasma and the remaining term is the rate at which helicity is injected or ejected from the boundary. Since the surface term in Eq. (1) contains the product of the toroidal flux ϕ with the toroidal voltage V_z, helicity can effectively be "injected" into the plasma if ϕ and V_z are sinusoidally oscillated in phase with one another, even though the time-averaged electric fields are zero.

The purpose of this work is to try to better understand the possible mechanisms underlying these relaxations within the context of different kinds of resistive MHD instabilities. In previous work,[4,5] we have shown that $m = 1$ helical perturbations are required if resistive MHD is the mechanism for the plasma current sustainment

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during OFCD. Furthermore, we have identified a class of $m = 1$ tearing modes that generate significant amounts of poloidal flux (a necessary condition for current drive). In this paper, we will search for evidence of the presence of these instabilities in OFCD discharges from ZT-40M.

II. MODEL

As mentioned in the previous section, a class of $m = 1$ tearing modes that satisfy the necessary criteria of increasing the poloidal flux and of inducing a dc emf on axis has been identified. The linear and nonlinear behavior of these instabilities was discussed in detail in a paper by Caramana, Nebel and Schnack.[6] These modes are driven unstable by an off-axis peak in the $J_{\|}/B$ profile and nonlinearly result in an increase in the poloidal flux (and a decrease in q on axis). Single-helicity nonlinear simulations have shown that the final globally reconnected state is well described by the Kadomtsev reconnection model.[6,7] Since the Kadomtsev interaction region[7] seldom extends to the reversal surface, these modes should not significantly affect the RFP "dynamo".

However, the RFP dynamics also include another type of instability that decreases the poloidal flux. These instabilities have been shown by many authors[6,8-14] to cause the so called "dynamo effect" in the RFP, which maintains the toroidal flux inside of the toroidal field reversal surface. The nonlinear evolution of these two kinds of instabilities (i.e. the dynamo mode and the current drive mode) is schematically represented in Fig. 1. In both cases, the $m = 1$ current-driven tearing modes tend to flatten the $J_{\|}/B$ profile, thus bringing the plasma closer to a Taylor relaxed state.[15]

A simple scenario for a single cycle of the OFCD oscillations can be constructed in terms of the evolution of the q profile, by considering the stability of the RFP configuration to the two above-mentioned kinds of $m = 1$ current-driven tearing modes. A schematic picture of the entire cycle is given in Fig. 2.

III. TRANSPORT SIMULATIONS OF THE OFCD DISCHARGES

We have simulated the MHD dynamics of the OFCD experimental discharges[16] using the combination of a 1-D transport model. Since all the oscillations are similar, only one cycle of the OFCD oscillations in a given discharge has been analyzed.

The purpose of the 1-D transport simulations is to determine if the $m = 1$ modes required for OFCD are present in the experimental data. First, the initial profiles for the magnetic field, temperature and density are specified consistently with the experimental measurements of density, temperature and the global parameters $F(F \equiv B_z(a)/ < B_z >)$ and $\theta(\theta \equiv B_\theta(a)/ < B_z >)$. These profiles are then evolved in time with a 1-D cylindrical transport code [17] in which the plasma configuration evolves through a series of equilibrium states. The applied boundary conditions are the experimentally measured toroidal magnetic field and electric field at the wall. The resultant waveforms of the toroidal flux and plasma current are then compared with the experimental values. Since both the RFP dynamo instabilities and the current drive instabilities are not describable by a 1-D, two-fluid transport model, disagreement between the simulation results and the experimental data strongly suggests that one of these types of instabilities is present. How the numerical simulation and the experiment disagree as well as the MHD stability of the calculated $J_{\|}/B$ profile will indicate which type of mode is the most likely.

If the toroidal magnetic flux in the simulation is less than the flux measured experimentally, then it is likely that the "dynamo" is present in the experiment. If the toroidal current in the simulation is less than the experimentally measured toroidal current and the simulation indicates the presence of an off-axis peak in the $J_{\|}/B$ profile that is unstable to $m = 1$ tearing modes which reconnect to the axis, then we interpret this result as indicating the presence of current drive modes. As will be shown below, this case does not occur in the simulations.

Because experimental resistivity profile information does not exist, we treat this profile as a free parameter. By performing transport simulations with different resistivity profiles, we try to make sure that differences between the results of the simulations and the experimental data are due to the plasma dynamics not modeled in the transport code (i.e. dynamo and current drive modes) rather than to resistivity profiles. For this reason, we have considered different resistivity profiles, that we have written in the form: $\eta(r,t) = \eta(0,t) \cdot \eta(r)$. The value of the resistivity on axis $\eta(0,t)$ is consistent with Spitzer's formula[18] ($T_e(0)$ is based on Thomson scattering,

$Z_{eff} = 2$).

Transport results are presented only for a high current, two-circuit oscillation discharge. We have simulated a number of different discharges under various conditions[5] with similar results. The cycle under examination is divided in two phases: one in which the toroidal flux ϕ increases and the other in which ϕ decreases. The profiles are initialized at the beginning of each phase to match the experimental data. The toroidal voltage and the magnetic toroidal field at the wall $B_z(a)$, used as boundary conditions for the transport simulation, are shown in parts (a) and (b) of Figs. 3 and 4. The average toroidal magnetic field $< B_z >$ and the plasma current I_z are presented in parts (c) and (d) as given by the experiment (solid line) and from our simulations (dots). As expected, we are not able to reproduce the waveform of the average toroidal field $< B_z >$ during the increasing flux phase, no matter how we change the resistivity profile. Thus, the RFP dynamo is apparently active during this phase.

During the decreasing flux phase, the compression of the plasma induces an off-axis current peak. However, even in our closest simulation (shown in Figs. 4 c,d), the toroidal flux lags the experimental value, suggesting that the dynamo may be present in this phase as well. Other simulations with different resistivity profiles showed an even larger discrepancy between the simulated and experimental toroidal fluxes.

The major problem present in every discharge we have examined, is that the "dynamo" appears to be active during the entire cycle. This seems to suggest the need of an increase in the swing of the toroidal flux or its frequency. In this way, the plasma compression will extend for most of the decreasing flux phase and the current peaks determined by the applied E_z and E_θ at the wall (roughly coincident with $E_\perp$ and $E_\parallel$) will add up. In the same phase, a higher value of E_θ will sustain J_θ from the boundary, thus slowing down the inward motion of the reversal point. Vice versa, during the increasing flux phase, a more negative value of E_θ will drive currents in the poloidal direction that will help maintain reversal against the plasma expansion.

In summary, a higher value of the poloidal voltage should remove the skin current from the plasma edge and should eliminate the RFP "dynamo" during the toroidal flux decreasing phase. The importance of the radial parallel current profile and of the ratio V_θ/V_z, has been deduced from the analysis of the 1-D transport simulations of the experimental data and cannot be predicted by the 0-D global helicity balance of Eq. (1).

IV. SUMMARY AND CONCLUSIONS

A scenario for a cycle of the OFCD oscillations has been developed in terms of the evolution of the q profile. The compression and expansion of the plasma, determined by the modulations of the applied toroidal and poloidal voltages, have been associated to two different classes of $m = 1$ current-driven tearing modes. One type of instability is driven unstable by off-axis current peaks and nonlinearly generates poloidal flux, which is a necessary condition for current drive; the other type of instability is driven unstable by on-axis current peaks and sustains the toroidal magnetic field configuration against resistive diffusion.

We have provided an interpretation of the experimental data. A Major issue is that the simulations indicate that the RFP "dynamo" may be continuously present during the entire cycle of the OFCD oscillations. An increase of the ratio V_θ/V_z from its low value in the present experiments should remove the skin currents localized in the outer edge of the plasma and eliminate the "dynamo effect" from the decreasing flux (current-drive) phase.

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REFERENCES

[1] M. K. Bevir and J. W. Gray, Proc. of the Reversed Field Pinch Theory Workshop, Los Alamos report No. LA-8944-C 76 (1981).

[2] K. F. Schoenberg, R. W. Moses, Jr., and R. L. Hagenson, *Phys. Fluids* **27**, 1671 (1984).

[3] M. K. Bevir, C. G. Gimblett, and G. Miller, *Phys. Fluids* **28**, 1826 (1985).

[4] R. A. Nebel, R. A. Scardovelli, K. A. Werley, G. H. Miley, D. S. Harned, H. R. Strauss, D. D. Schnack, and Z. Mikic, Proc. 11th Int. Conf. on Plasma Physics

and Controlled Nuclear Fusion Research, paper D-V-12, Kyoto, Japan (1A86) IAEA Vienna.

[5] R. A. Scardovelli, Ph. D. Thesis, University of Illinois, Urbana, Illinois (1987).

[6] E. J. Caramana, R. A. Nebel, and D. D. Schnack, *Phys. Fluids* **26**, 1305 (1983).

[7] B. B. Kadomtsev, *Sov. Plasma Phys.* **1**, 389 (1975).

[8] D. D. Schnack, E. J. Caramana, and R. A. Nebel, *Phys. Fluids* **28**, 321 (1985).

[9] A. Sykes and J. A. Wesson, in Proceedings of the 8th European Conference on Controlled Fusion and Plasma Physics, Prague, 1977 (Czechoslovak Academy of Sciences, Prague, 1977), p. 80.

[10] A. Y. Aydemir and D. C. Barnes, *Phys. Rev. Lett.* **52**, 930 (1984).

[11] H. R. Strauss, *Phys. Fluids* **27**, 2580 (1984).

[12] A. Y. Aydemir, D. C. Barnes, E. J. Caramana, A. A. Mirin, R. A. Nebel, D. D. Schnack, and A. G. Sgro, *Phys. Fluids* **28**, 898 (1985).

[13] J. A. Holmes, B. A. Carrerras, T. C. Hender, H. R. Hicks, V. E. Lynch, Z. G. An, and P. H. Diamond, *Phys. Fluids* **28**, 261 (1985).

[14] R. Horiuchi and T. Sato, *Phys. Rev. Lett.* **55**, 211 (1985).

[15] J. B. Taylor, *Phy. Rev. Lett.* **33**, 1139 (1974).

[16] K. F. Schoenburg, G. A. Wurden, P. G. Weber, J. C. Ingraham, C. P. Munson, D. A. Baker, C. J. Buchenauer, L. C. Burkhart, T. E. Cayton, J. N. DiMarco, J. N. Downing, R. M. Erickson, P. R. Forman, A. Haberstich, R. B. Howell, F. C. Jahoda, R. S. Massey, G. Miller, R. W. Moses, Jr., R. A. Nebel, J. A. Phillips, M. M. Pickrell, A. E. Schofield, R. G. Watt, D. M. Weldon, K. Werley, Proc. 11th Int. Conf. on Plasma Physics and Controlled Nuclear Fusion Research, paper D-II-3, Kyoto, Japan (1986) IAEA Vienna.

[17] K. A. Werley, R. A. Nebel, and G. A Wurden, *Phys. Fluids* **28**, 1450 (1985).

[18] L. Spitzer, Jr., Physics of Fully Ionized Gases (Wiley, New York, 1962), p. 73.

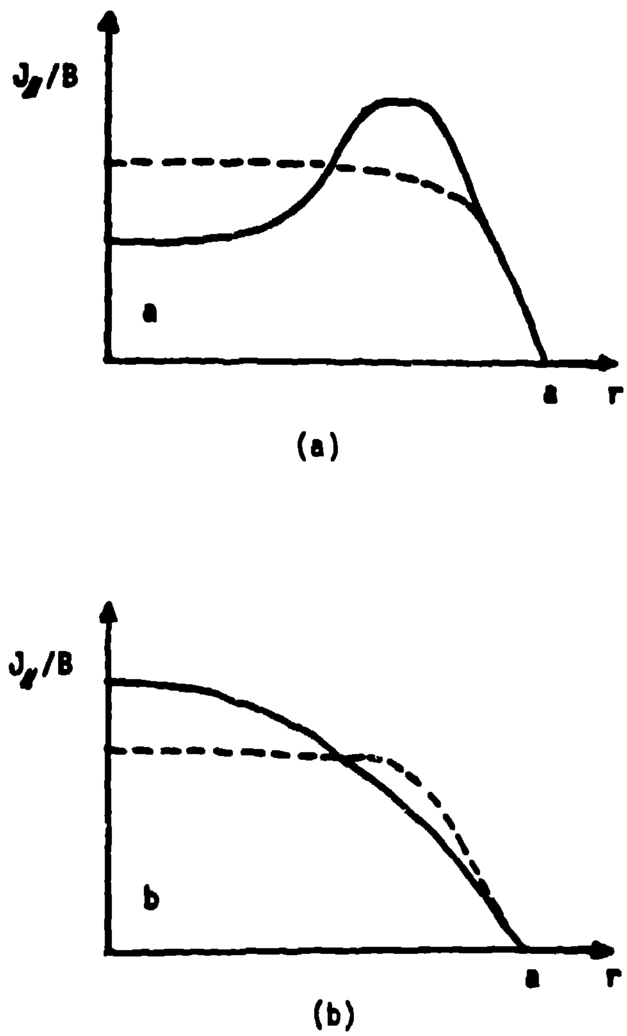

Fig. 1. Schematic evolution of unstable peaks in the $J_{\parallel}/B$ profile: a) inward flattening of an off-axis peak (current penetration mode), b) outward flattening of an on-axis peak (dynamo mode).

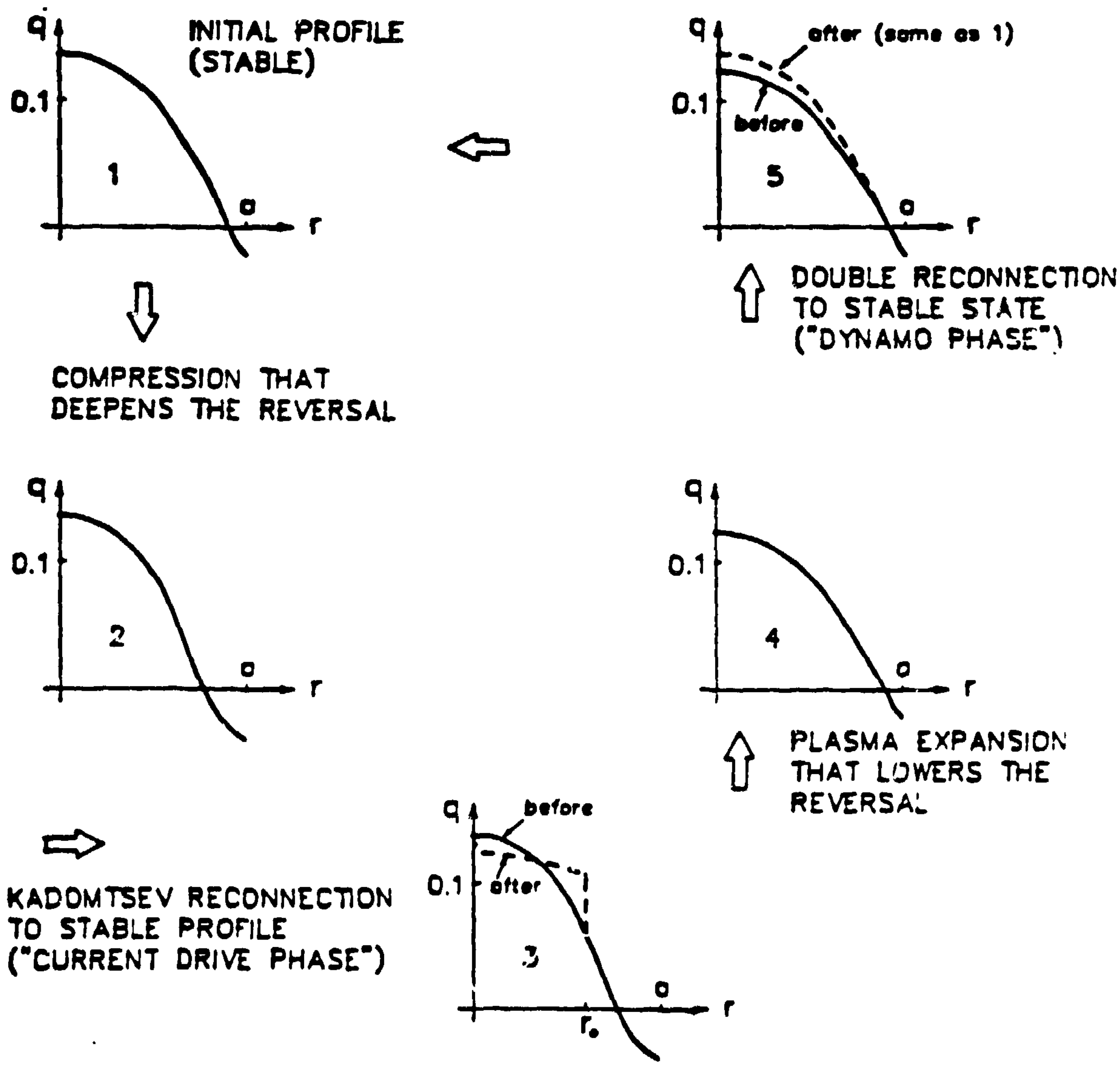

Fig. 2. Scenario for a cycle of the OFCD oscillations.

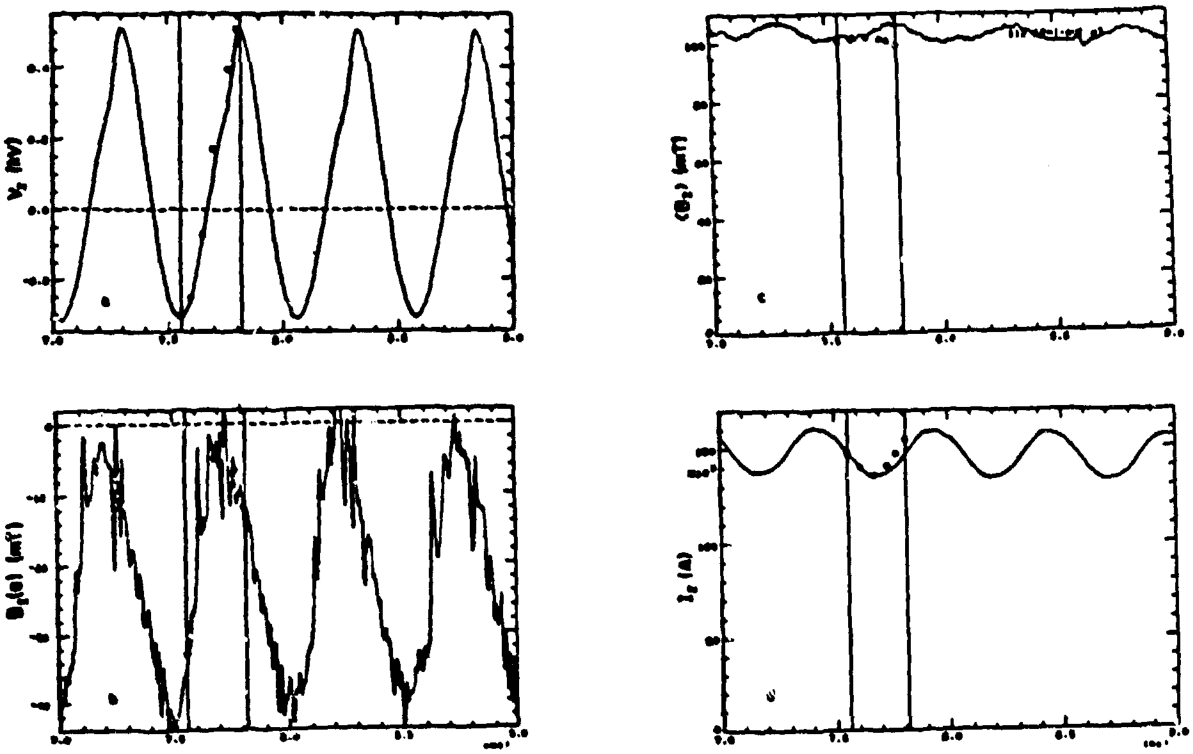

Fig. 3. Shot number 22073. High current, two-circuit oscillations. Increasing flux phase. Boundary conditions: a) toroidal voltage, b) toroidal magnetic field at the wall, c) average toroidal magnetic field, and d) plasma current.

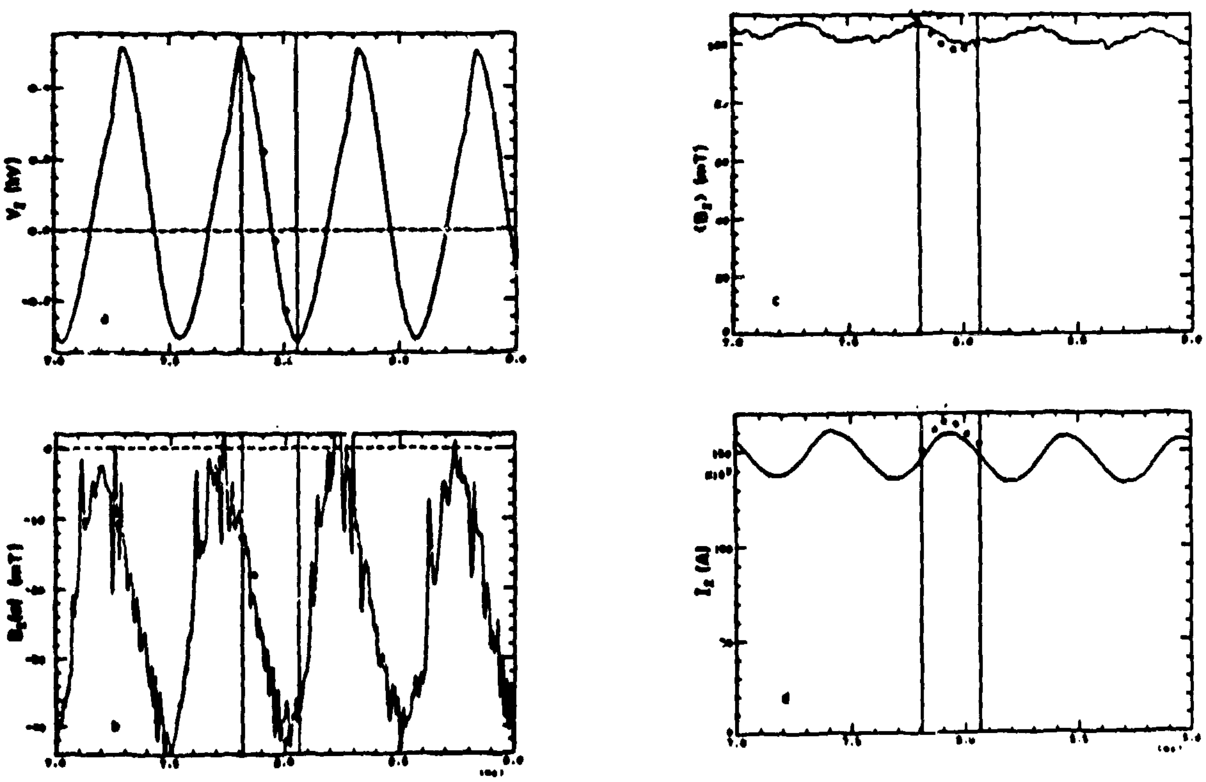

Fig. 4. Shot number 22073. High Current, two-circuit oscillations. Decreasing flux phase. Boundary conditions: a) toroidal voltage, b) toroidal magnetic field at the wall, c) average toroidal magnetic field, and d) plasma current